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AN OBJECTIVE METHOD FOR FORECASTING PRECIPITATION AMOUNTS FROM WINTER COASTAL STORMS FOR BOSTON

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INTRODUCTION

The problem of precipitation forecasting in New England has been emphasized by the needs of the many varied industries of that region for accurate forecasts when rain or snow is in prospect. Some are especially interested in the type of precipitation, others in amounts. Among those which become extremely dependent upon estimates of the amount of future precipitation in directing their operations are the power and light companies, transportation interests, the U. S. Engineers, and others. Because of this need for forecasting service, the newly established Weather Bureau forecasting research unit at Boston initiated the project described in this paper; the problem of forecasting the type of precipitation was not included in the project, since it is a separate one and fully as complex as that of forecasting amounts.

In this study an attempt was made to combine the techniques of several previous studies and apply them to the particular problem of forecasting for Boston the precipitation amounts to be expected from winter coastal storms. Earlier investigations by Rodgers [1] and by Miller [2], which were concerned with the typing and the recognition of pressure patterns which lead to Atlantic coastal developments included no attempt to evaluate quantitatively the resultant precipitation. Brier [3], however, demonstrated in his study of the T. V. A. Basin that objective techniques could be successfully employed in making quantitative forecasts of precipitation.

This study, patterned loosely after Brier's investigation, was made with a threefold objective:

1. To develop a practical method for computing the precipitation amounts from coastal storms, using data available at the time of the forecast.
2. To show the relative values of the factors contributing to the computation of precipitation amounts.
3. To test the reliability of specific factors now favored by some of the Boston forecasters in determining precipitation amounts.

Briefly, the method employed to gain this objective consisted of choosing several indices in the synoptic field, both at the surface and at upper levels, which were concurrent with the first appearance of a storm in the coastal area. These were related graphically to subsequent amounts of precipitation recorded.

Data used in the study were for the months of November, December, January, February, and March for the five winters of 1942–43, 1943–44, 1944–45, 1945–46, and 1946–47. For an independent check study, data of November 1942, January 1943, December 1944, February 1946, and March 1947, were set aside. These data were selected so that each month would be represented by data from a different year. In all, 96 storms were studied to develop the computation charts and 24 storms to test the results. Although the investigation of precipitation data was restricted to precipitation amounts resulting from coastal storms, it was found that the greater and most important portion of winter precipitation for southern and central New England was covered. Examination showed that 80 percent of the total winter precipitation and nearly all amounts in excess of 0.35 inch resulted from coastal storms. In addition, and somewhat contradictory to the belief that coastal storms are accompanied by heavy amounts of precipitation, actual observation (see Figure 1) showed that in 25 percent of the cases included in the 5-year study the resultant rainfall was less than ¼ inch; in only 25 percent of the cases did the amounts equal 1 inch or more.

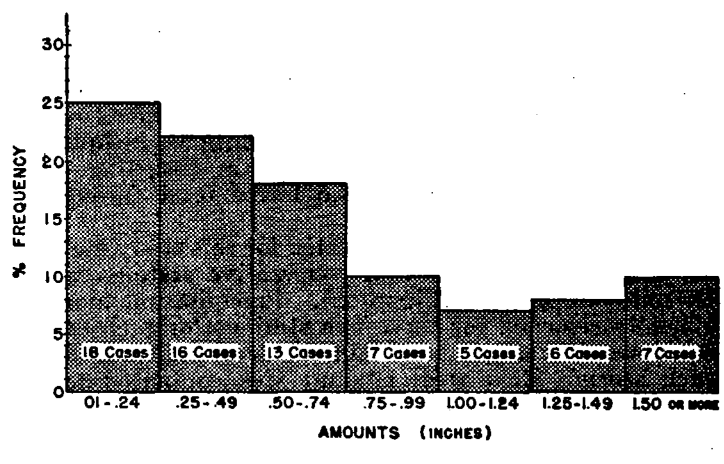

FIGURE 1.—Frequency distribution of observed amounts of precipitation in the Boston area resulting from coastal storms which occurred during the 5-year period of investigation.

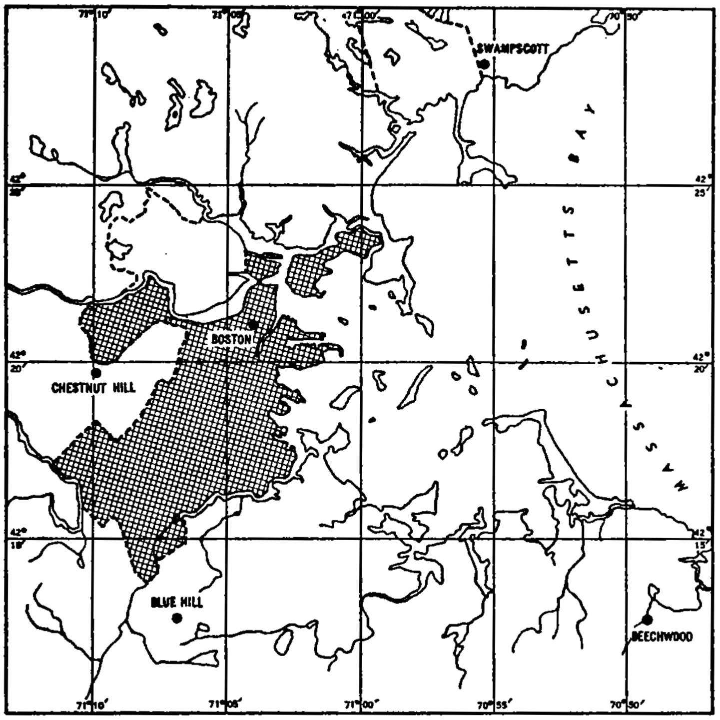

FIGURE 2.—Map showing stations in the Boston area used to obtain representative observed precipitation amounts for coastal storms.

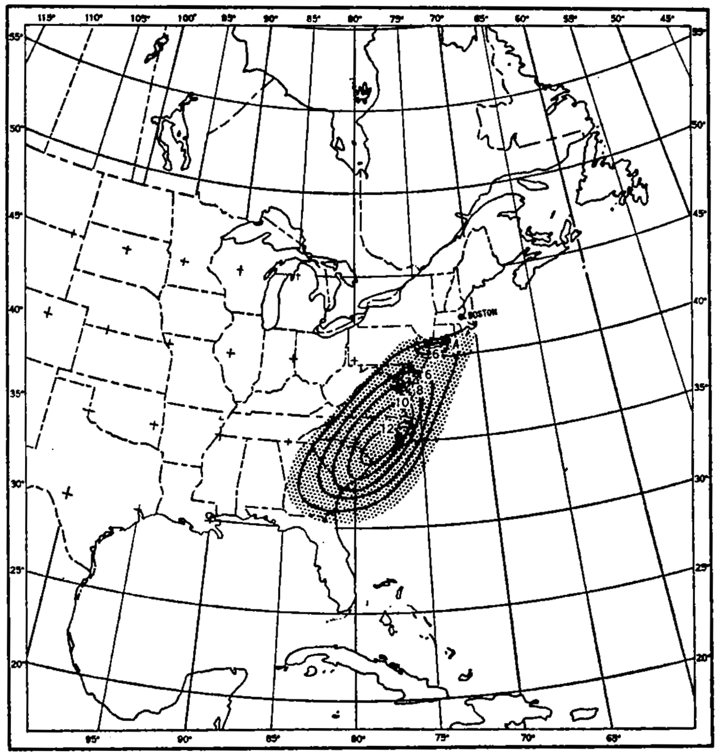

FIGURE 3.—Map with isopleths showing relative distribution of storms within the Atlantic Seaboard area (shaded portion).

It should be pointed out that since not all of the factors affecting precipitation could be evaluated, the computations in this paper yield only an approximate, but nevertheless useful, solution to the forecasting problem. Although encouraging results can be obtained by exclusive use of the suggested techniques, forecasts are often complicated by interactions, accelerations, and developments on the weather map which require considerable subjective consideration. Therefore, the simple, objective technique presented here should not be considered a complete method of forecasting *per se*, but rather an auxiliary tool for the forecaster which will allow him to evaluate properly several of the important meteorological variables. Best results in forecasts, however, can be obtained by not losing sight of the unevaluated factors.

DEFINITION OF TERMS

As a preliminary step to examining the data to be used, it was necessary to decide upon the limitations of the study. The following resulting definitions include explanations of the factors involved in assigning these specific meanings to the basic terms used throughout this presentation.

Forecast area.—The area selected for this study included the Boston Airport and four cooperative stations within 10 miles of Boston (Figure 2). Precipitation amounts officially reported for these five stations for each coastal storm were averaged to obtain the areal precipitation for each storm. This areal amount was computed for all storms which occurred in the 5-year period and was used as the Boston precipitation in the study. For this period it was found that precipitation amounts varied little over the area. The correlation coefficient, for example, between the recorded amounts at Boston and at Chestnut Hill (a cooperative station about 5 miles west) was computed at 0.97.

Precipitation amounts.—These amounts are storm totals rather than fixed-period amounts, since the totals are more significant and useful and they also simplify the study. All precipitation amounts greater than 1.49 inches were classed in one group and assigned the value of 1.50 inches, the value which was used for verification purposes.

Coastal storm.—A coastal storm was defined as the presence at the surface level along the Atlantic Seaboard (shaded area of Figure 3) of either (a) a definite wave formation in the front, (b) a cyclonic wind field, or (c) a closed low. In addition, it was required that there be a center of 3-hourly pressure falls associated with the wave or storm. The study was not limited to storms which originated in the prescribed coastal area but included those which might have moved into the Atlantic Seaboard from any direction. However, of the 125 storms included in the basic and test data, 115 were true secondaries, or new developments within the prescribed area.

In order to determine the favored locations of coastal developments, the area along the Atlantic Seaboard was analyzed with regard to the number of storms found in overlapping sections 2 degrees latitude by 2 degrees longitude in dimension. The value, then of an isopleth at any point in Figure 3 indicates the number of storms whose origin or point of entry into the coastal area was located within a section centered at that point and bounded by meridians and parallels 2 degrees apart. Figure 3 shows that there is an area of maximum occurrence between Hatteras and Charleston and a minor secondary maximum near Long Island.

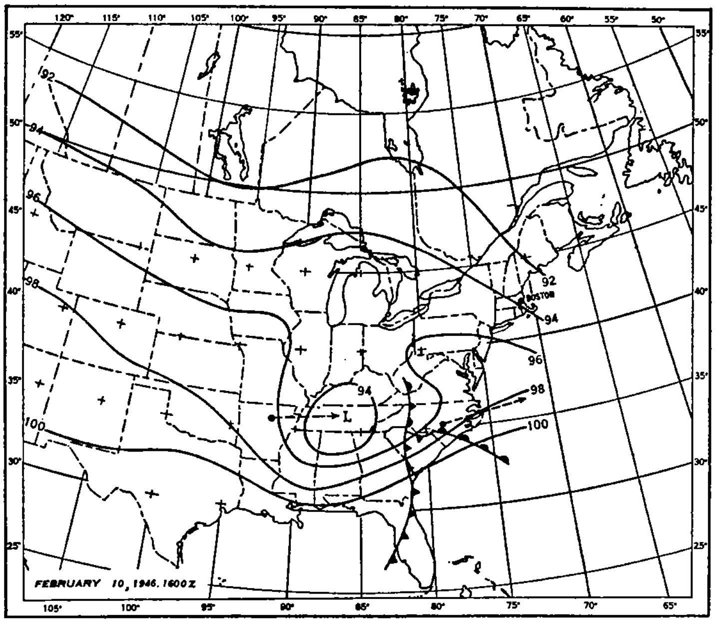

FIGURE 4.—700-mb. chart showing a pressure pattern with a closed low southwest of Boston which would not influence the circulation over Boston. (Arrows and dashed line indicate past 12-hour movement of the low center.)

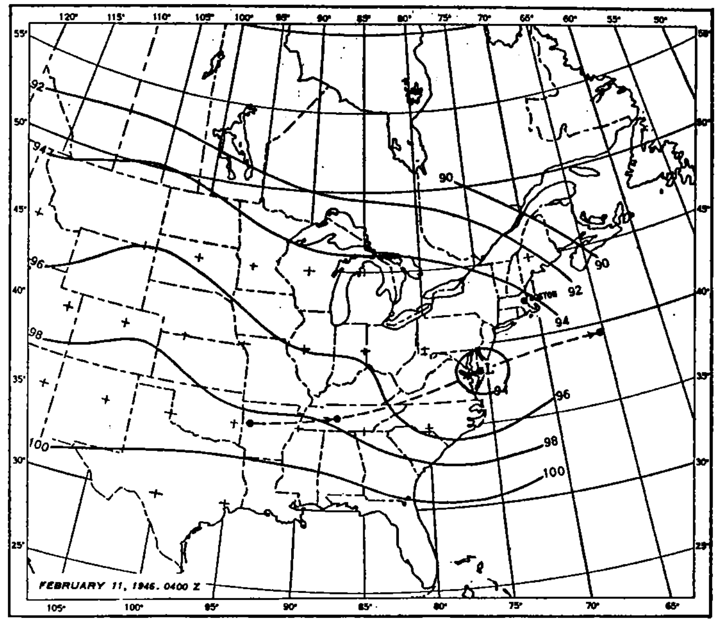

FIGURE 5.—700-mb. chart showing the pressure pattern existing 12 hours later than that in Figure 4. (Arrows and dashed lines indicate past two 12-hour movements of the low center.)

METHOD OF INVESTIGATION

SELECTION OF VARIABLES

In selecting the meteorological variables to be related to observed precipitation amounts, the results of previous research and the experience of other forecasters formed a partial basis for consideration. In one investigation, for instance, Petterssen [4] concluded that coastal storms seem to develop in the lower levels of the atmosphere, where air mass contrasts are greatest and wind fields are most favorable. This conclusion directed attention to the requirement for selecting variables in the lower atmosphere which expressed a measure of the potential strength of developing storms, and those in the upper levels which pointed to the contribution made by the primary storm or trough to the coastal development.

Primarily, however, the independent variables were selected on the basis of a study of many individual storms, using data in each case obtained from the 6-hourly synoptic surface map and the latest available upper-air charts preceding it. To find variables, both at the surface and at upper levels, which appeared to be particularly significant to the problem of forecasting amounts of precipitation, it was necessary to look for those which expressed (a) some indication of the precipitation amounts which occurred near the center of the storm, or (b) some indication of the path of the storm with relation to the forecast area. The latter consideration is, of course, important to the amount of precipitation to be forecast, since it is obvious that the passage of an intense storm far to the east of Boston, for example, will give only a small amount of precipitation at that station.

Finally, the selected independent variables were divided into two groups: (1) the primary variables, which were applied to all storms; (2) the secondary variables, which were applied selectively according to the surface pressure pattern over the eastern portion of the storm map.

Primary variables.—The primary variables were labeled and defined as follows:

X_1 The 850-mb. wind direction immediately over the surface storm. This is a partial measure of the influx of warm, moist air to be expected. In the absence of actual wind observations, this variable was estimated, using pibal data from nearby stations and the geostrophic wind.

X_2 The 700-mb. contour direction immediately over the surface storm. This variable indicates to some extent (a) convergence due to the latitude effect; (b) orientation of the 700-mb. trough; and (c) direction of movement of the surface storm.

X_3 The latitude of the surface storm. The largest amounts of precipitation were found to accompany these storms which develop farthest to the south, other factors being equal.

X_4 The minimum latitude reached by following the 700-mb. contour upwind through Boston no farther than 95° W. long., which indicates to some extent the amplitude of the 700-mb. trough. Where this contour did not go south of Boston between Boston and 95° W. long., the variable was defined as the latitude where the contour crossed the 95th meridian.

Its determination is not objective when a closed low is found to the southwest of Boston, and the contour through Boston, instead of extending southwestward to the low, reaches westward or even northwestward.

Given this situation, the forecaster must decide on the basis of his experience whether Boston will remain in the westerly flow or will come under the influence of the low pressure to the southwest; furthermore, this decision, an all-important one, must be made by the forecaster whether or not he embodies objective techniques in his forecast. For the purpose of this study, however, the value

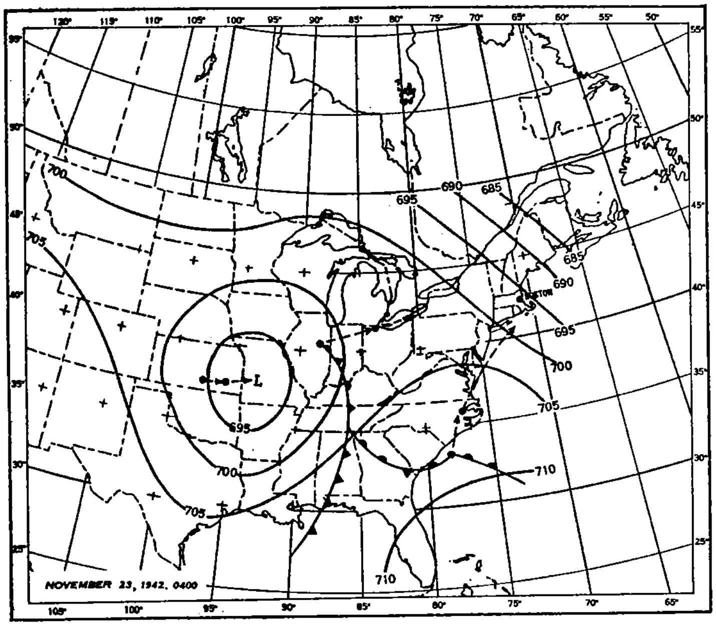

FIGURE 6.—10,000-foot map showing a pressure pattern with a closed low southwest of Boston which presages a change in the circulation over Boston. (Arrows and dashed lines on left show past two 12-hour movements of low center.)

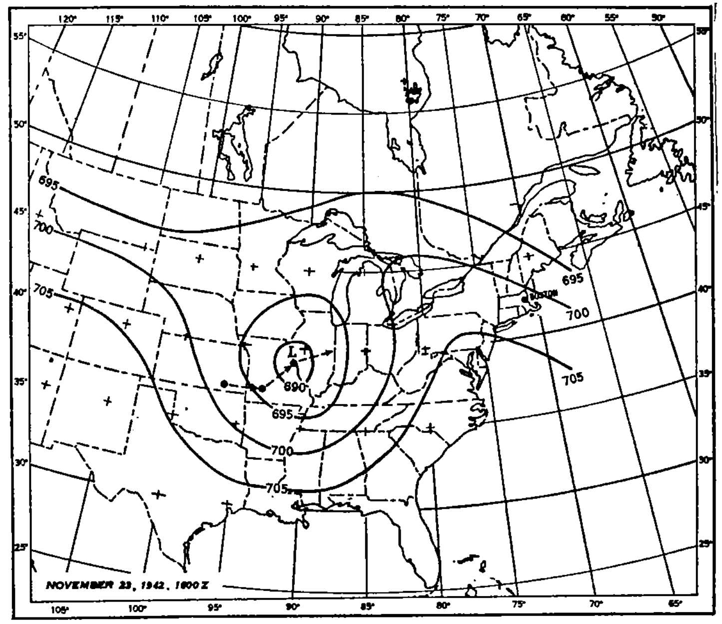

FIGURE 7.—10,000-foot map showing the pressure pattern existing 12 hours later than that in Figure 6.

X_4 for the 15 cases involving a closed low southwest of Boston (as, for example, those shown in Figures 4 and 6) was determined by looking ahead at subsequent maps, although the forecast procedure would usually be objective and straightforward.

In Figure 4 the arrows and dashed line indicate the previous 12-hour movement of the low, which was rapid and eastward; the easterly circulation of the trough extends only to 38° N. lat. Simple extrapolation of the low pressure movement indicated that it would continue eastward without disturbing the westerly flow over Boston. This was verified by a look at the 700-millibar map 12 hours later (Figure 5). The value for X_4 in this example was 47°.

Figure 6, on the other hand, is an example of an upper-air chart which does presage a change in the circulation over Boston. Here the low (the past two 12-hour movements shown by arrows and dashed lines) is seen to be moving very slowly eastward, and the easterly circulation extends to about 45° N. lat. The value of 32° was assigned to X_4, since the 700-mb. isobar moving up to Boston was expected to become part of the 700-mb. isobar to the southwest. Figure 7, which shows the pressure pattern 12 hours later, verified this.

Secondary variables.—The secondary variables selected were sea level pressure distribution patterns found on storm maps. They were labeled and defined as follows:

Type 1 (a) There is present on the surface map a center of high pressure north or northwest of New England, with a wedge extending southward into New York, Vermont, or New Hampshire;

(b) the past 12-hour movement of the wedge near 45° N. lat., has been 250 miles or less;

(c) the sea level pressure at Caribou, Maine, is at least 15 mb. higher than the pressure at Gander, Newfoundland;

(d) there is a second high-pressure center within 5 degrees of latitude south of Bermuda.

The pressure pattern of Type 1 (exemplified by Figure 8) shows the orientation of the two highs with a col or trough near 32° to 39° N. lat., a favored path for coastal storms. The specific Caribou-Gander pressure difference indicates the presence of the force necessary to propel the storm eastward between the two highs. The greater this difference, the sooner the storm can be expected to recurve, and Type 1 maps are associated with storms which recurve to the east while still south of Long Island. They give southern New England less precipitation than would be forecast using only the primary variables.

Type 2 When the surface map did not fulfill the conditions of Type 1, it was examined for Type 2 criteria. In this type (Figure 9) a center of high pressure must be north of 41° N. lat., and to the north or northeast of the coastal storm. When the high center is east of north with relation to the storm, a westward extension of the ridge must be north of the storm. This pressure pattern

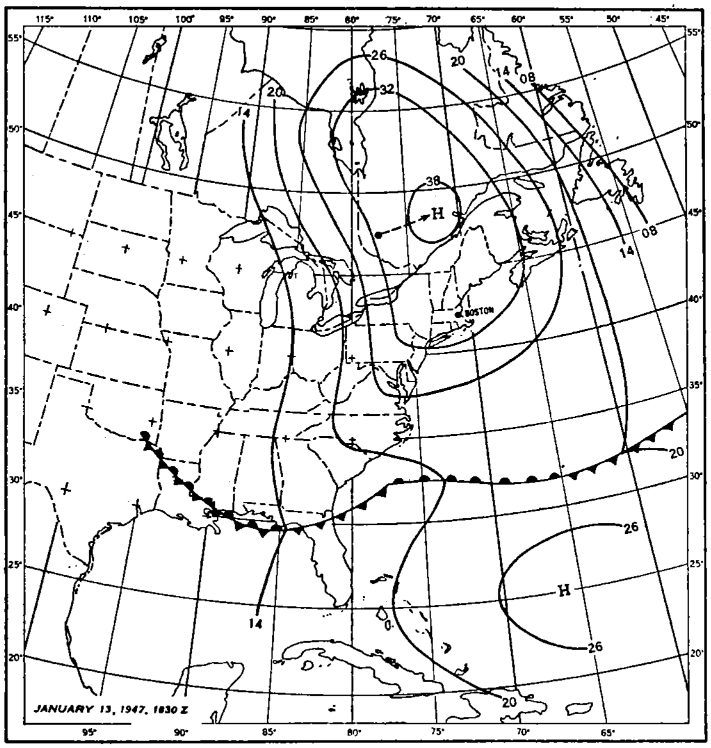

FIGURE 8.—Surface map showing Type 1 pressure distribution, associated with storms that recurve to the east while south of Long Island.

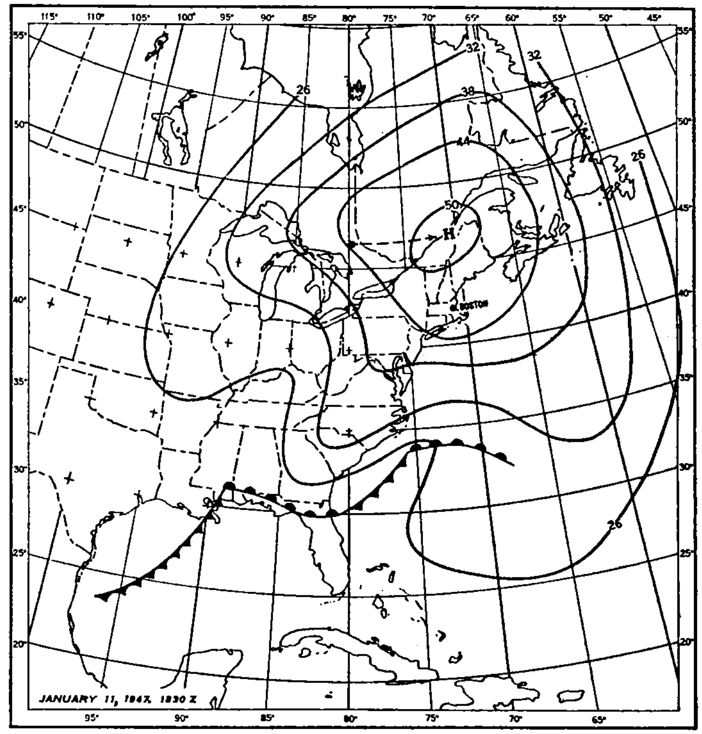

FIGURE 9.—Surface map showing Type 2 pressure distribution, associated with more slowly moving storms.

is necessarily accompanied by slow movement of the storm, due to blocking action of the high. Therefore, Type 2 indicates a longer period of precipitation than would be forecast using only the primary variables. It is interesting to note that only six storms of the 5-year study resulted in precipitation amounts greater than 2 inches, and all six were associated with maps classified as Type 2.

Type 3 All maps not meeting the requirements of Types 1 or 2 were generally classified as Type 3. In this type (Figure 10) the wave was found on the west side of the Atlantic high cell, with no wedge in the apparent path of the storm. Isobars from the wave northward were oriented in a south-north or southwest-northeast direction. Such a pressure distribution favors rapid movement of the storm and therefore lesser amounts of precipitation than would be forecast using only the primary variables.

There are occasionally situations for which it is difficult to distinguish between Type 2 and Type 3 pressure patterns or in which Type 2 is changing to Type 3. In those cases the objective forecast is based only on the primary variables.

CLASSIFICATION OF MAPS WITH RELATION TO PRECIPITATION OCCURRENCE

Before relating the selected variables to observed precipitation amounts, it was necessary to stratify the synoptic surface maps used in the investigation according to whether or not they indicated that precipitation could be expected to occur at Boston. A procedure similar to that used by Brier in his T. V. A. study was employed. Whenever a storm was found in the prescribed coastal area on any surface map, the contour passing through Boston and the one passing through Block Island were each taken from the corresponding 700-mb. chart and traced on the map. When the contouric channel thus delineated on the surface map intersected, east of the 90th meridian, an area of precipitation associated with a low pressure center or a front, the map was placed in Group A; when the contouric channel did not cross such a precipitation area, the map was placed in Group B.

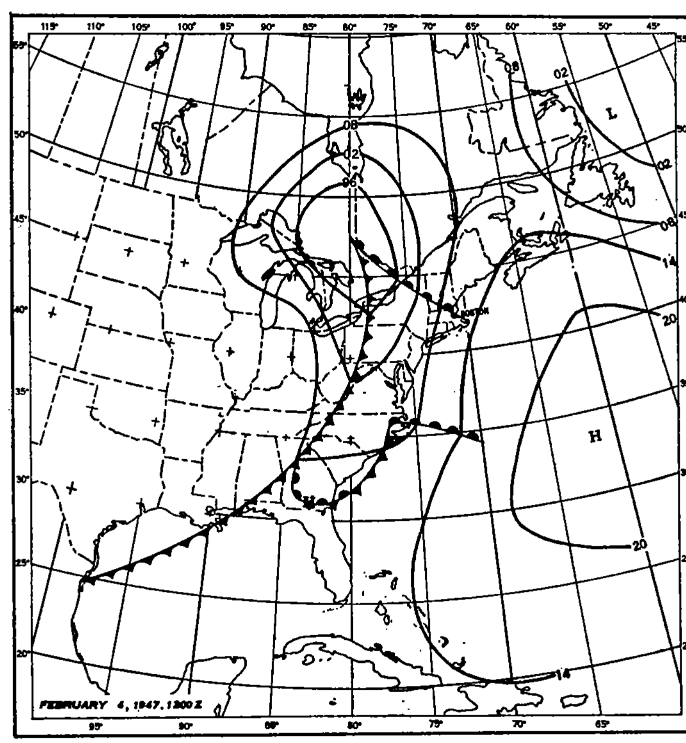

FIGURE 10.—Surface map showing Type 3 pressure distribution, associated with faster-moving storms.

Upon examination it was found that precipitation occurred subsequently at Boston for every Group A case (Table 1), whereas only 6 Group B cases resulted in precipitation, while 24 had none. Obviously, no additional

TABLE 1.—*Preliminary stratification of storm maps into those showing occurrence and nonoccurrence of precipitation*

	Map group A	Map group B
Precipitation	66	6
No precipitation	0	24

subdivision of Group A cases was necessary, but Group B cases needed further stratification. This was accomplished by plotting graphically the minimum latitude reached by the 700-mb. contour through Boston, variable X_4, against recorded amounts of precipitation. Figure 11 shows that all but two cases were followed by precipitation when X_4 was 38° or less, whereas only one case was followed by precipitation when X_4 was greater than 38°, and then the amount was only 0.07 inch. Therefore, those cases in which X_4 was 38° or less were relabeled Group B_1, and together with Group A cases were used in applying the selected primary and secondary variables to determine amounts of precipitation to be expected. Those cases having an X_4 value greater than 38° were relabeled Group B_2, and a forecast of no precipitation was assigned to them.

Since application of the criterion described above depended upon precipitation areas as far west as the Mississippi River, it suggested that a close relationship exists between primary and secondary storms. Previously, other investigators, including Brunt [5] and Austin [6], have pointed to a close relationship existing between the deepening of the wave and its accompanying cloudiness and precipitation. Petterssen, Austin, et al. [7] and others [8, 9] have also investigated many aspects of secondary cyclones on the Atlantic Coast. Experience too has supported this implied relationship, since it has shown that the two belts of precipitation associated with the primary and secondary storms, respectively, often merge into one, which appears to be moved along by the upper-level flow associated with both. The heaviest precipitation usually has been found to accompany the developing secondary, a fact also indicated by the data of this study. However, although this implied relationship should be noted in passing, it is beyond the scope of this paper to attempt an explanation of the physical and dynamical relationship between the primary storm and its secondary.

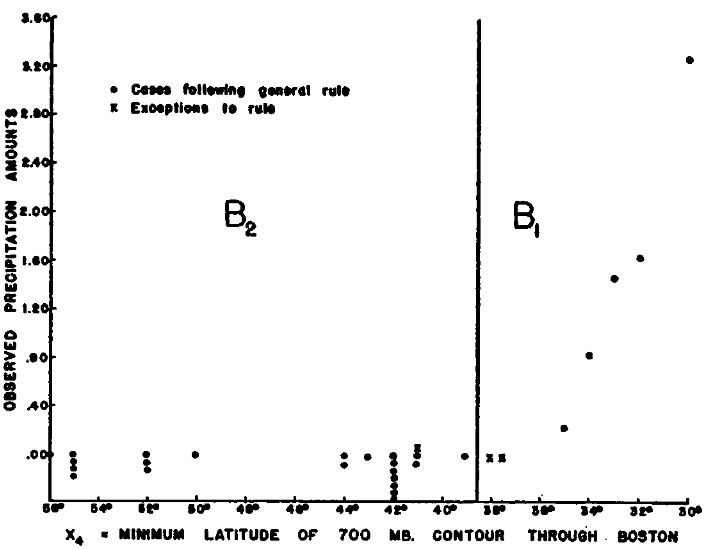

FIGURE 11.—Stratification of B map cases (see Table 1) into B_1 and B_2 cases by application of variable X_4.

CONSTRUCTION OF COMPUTATION CHARTS

Application of the variables to recorded precipitation amounts for the storms connected with the A and B_1 map classifications was accomplished in the manner shown in the schematic diagram of Figure 12. The general procedure was to work with the variables in pairs. For example, the terms X_1 and X_2 were used to derive the function Y_1; terms X_3 and X_4 were used to derive the function Y_2. In turn, these functions, Y_1 and Y_2 were combined to obtain the function Z, which was then modified, when necessary, by applying the appropriate secondary variable. The final result was the computed precipitation amount, C.

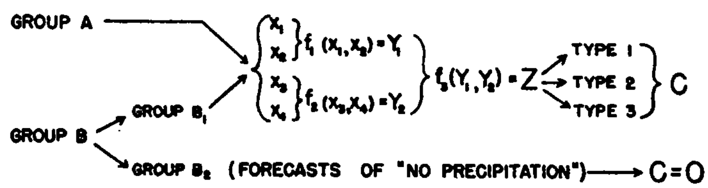

FIGURE 12.—Schematic working plan showing the steps in making an objective forecast from the preliminary classification of the map to the final computation of precipitation forecast value C.

The specific procedure in determining the dependence of precipitation amounts upon the several variables involved three steps. First, for each case the value of X_1 was plotted as the abscissa and the corresponding value of X_2 as the ordinate on a scattergram, and the point was labeled with the observed precipitation amount (Figure 13). Secondly, the scattergram was then marked off into cells of several observations each, with the mean of each cell entered in large figures within its limits. Thirdly, isopleths of precipitation amounts were drawn to these mean figures, keeping the lines as smooth as possible. From the isopleths in Figure 13 it is evident that X_1 (the 850-mb. wind direction above the storm) and X_2 (the 700-mb. contour direction over the storm) exert about equal effects upon the precipitation amounts.

Using X_3 and X_4 in place of the former variables, Figure 14 was constructed in the same manner. Since the isopleths in most portions of the chart tend to approach the horizontal, it can be assumed that the influence of X_3 (the latitude of the surface storm) generally is not as effective as X_4 (the minimum latitude of the 700-mb. contour through Boston).

Figure 15 shows the derivation of the function Z, determined by plotting functions Y_1 and Y_2 against each other, and indicating on the chart the corresponding amounts of observed precipitation. Isopleths of amounts were drawn, using the technique applied to the two previous charts.

The function, Z, thus derived from computation based on the four primary variables, was then modified by application of the appropriate secondary variable. Figure 16 was constructed with reference to modification necessary in Type 1 cases (see Figure 8). In this diagram the computed amounts of precipitation (Z values) were plotted against the observed amounts, with the corresponding values of the Caribou-Gander sea level pressure differences indicated. Two isopleths were drawn by inspection, one for 15 mb., and one for 20 mb. The 20-mb. curve was used for all values 20 mb. or greater; pressure differences below 15 mb. did not, by definition, fall into the Type 1 classification. Since the ordinate of this diagram expresses the final corrected values (as well as observed amounts), the chart is entered by following the line for the computed Z value upward until it intersects the proper pressure-difference curve. The ordinate value at this point of intersection represents the final computed precipitation amount (C) to be forecast. The slope of each of these pressure curves is less than one, indicating that too much precipitation would be forecast using only the primary parameters, unmodified by application of the secondary variables. This effect—precipitation amounts less than the average for coastal storms—would be expected from a Type 1 pressure field.

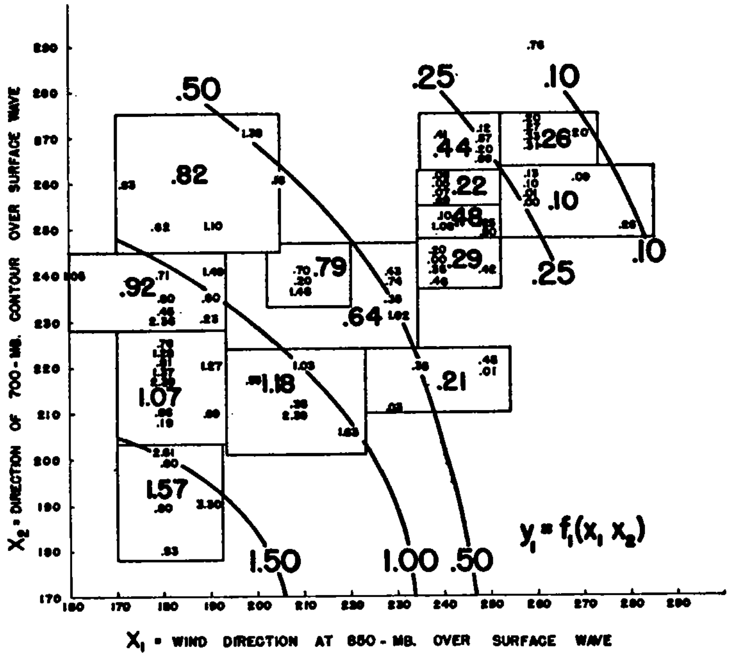

FIGURE 13.—Chart showing derivation of Y_1, a function of primary variables X_1 and X_2.

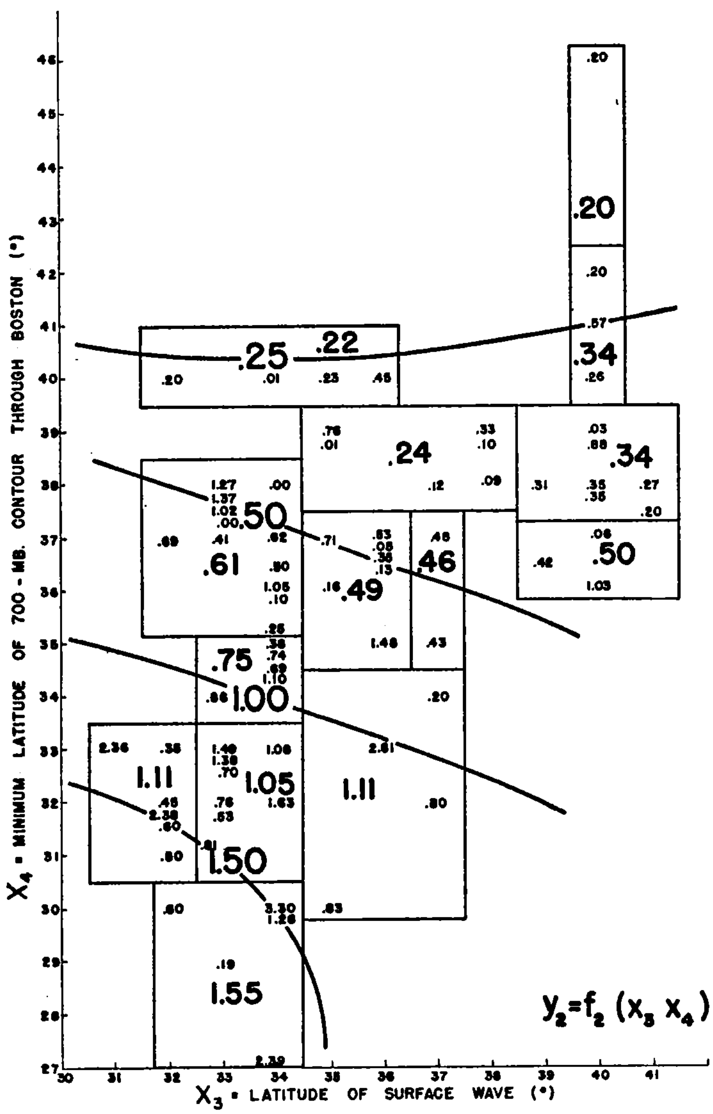

FIGURE 14.—Chart showing derivation of Y_2, a function of primary variables X_3 and X_4.

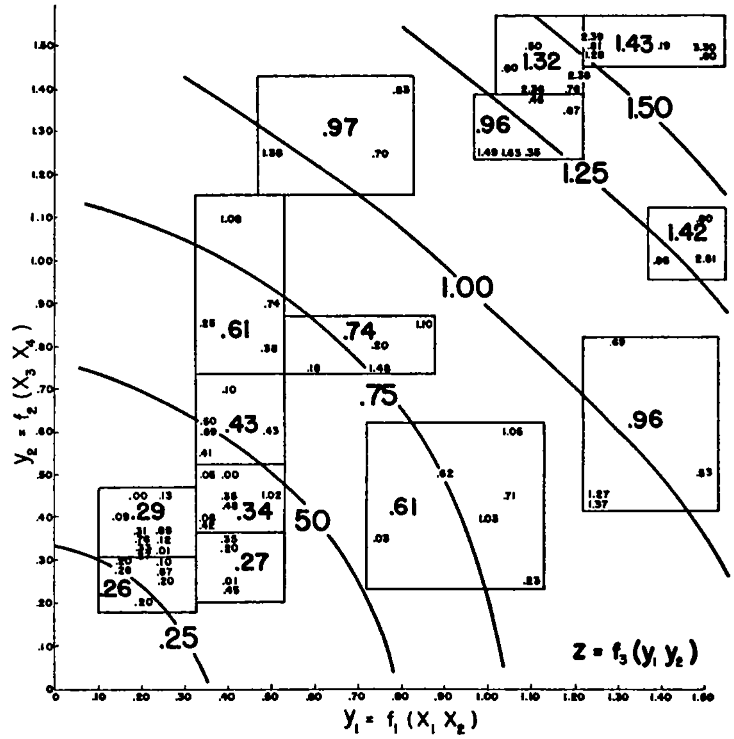

FIGURE 15.—Chart showing derivation of Z, a function of derived values of Y_1 and Y_2.

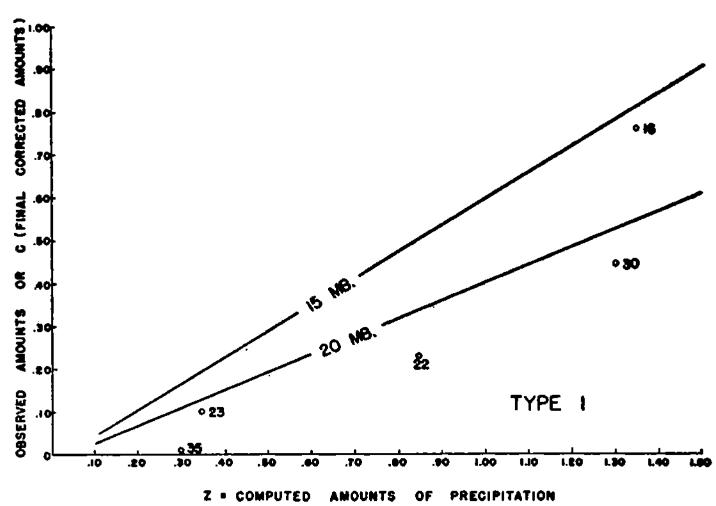

FIGURE 16.—Chart showing isopleths indicating necessary modification of Z values (computed amounts of precipitation) to obtain C values (observed or corrected amounts) for forecasting Type 1 cases.

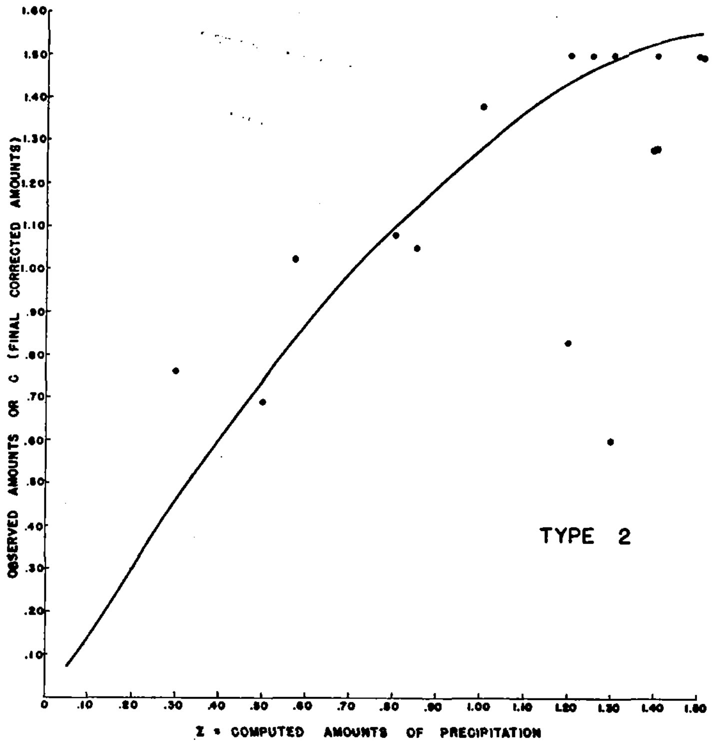

FIGURE 17.—Chart showing regression curve indicating necessary modification of Z values (computed amounts of precipitation) to obtain C values (observed or corrected amounts) for forecasting Type 2 cases.

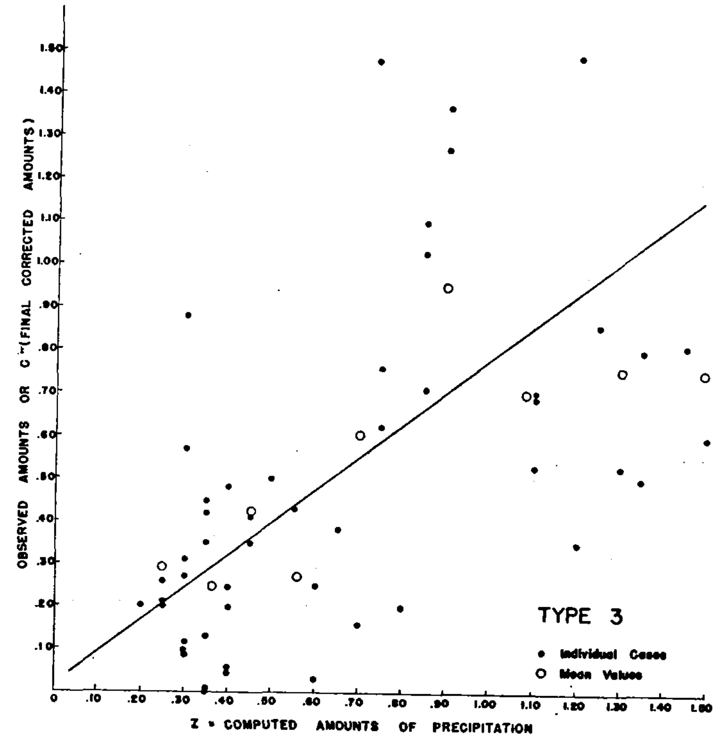

FIGURE 18.—Chart showing regression curve indicating necessary modification of Z values (computed amounts of precipitation) to obtain C values (observed or corrected amounts) for forecasting Type 3 cases.

In Figure 17, the computed amounts (Z) for all Type 2 cases (see Figure 9) were plotted against the observed amounts of precipitation, and a resultant regression curve was fitted by inspection to the individual points. The average slope of this curve is greater than one, indicating that insufficient precipitation would be forecast if only primary variables were used. This result is consistent with forecasting experience in Type 2 cases, where the blocking high cell in the path of the storm results in prolonged and therefore larger amounts of precipitation than are otherwise indicated.

Figure 18, for Type 3 cases (see Figure 10), was also constructed by plotting the computed amounts against the observed amounts of precipitation, the regression curve being obtained by using group averages. Its slope is less than one, a result in agreement with the observed results of fast-moving storms, which ordinarily give less precipitation than would be computed from application of the primary variables alone.

Finally, the observed amounts were plotted against the computed forecast amounts (C) for all cases (Figure 19), and the regression curve was obtained by using group averages. The resulting correlation coefficient was 0.84, with a standard error of estimate of 0.15 inch. It was noted that a correlation coefficient of 0.73 between the above computed amounts and the observed amounts at New Haven suggested that these charts could be applied with almost equal efficacy to most of southern New England.

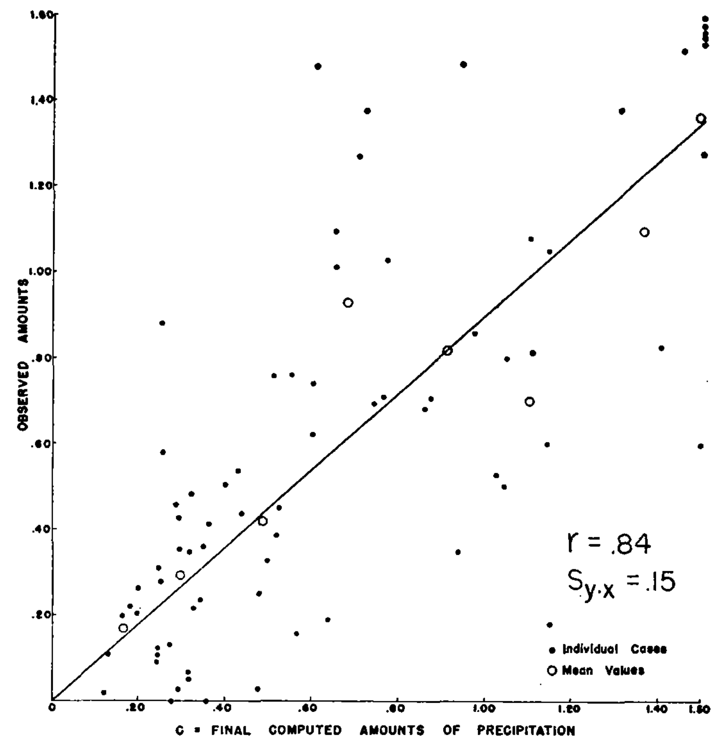

FIGURE 19.—Chart showing correlation of individual cases and mean values of observed precipitation amounts with final computed values for all storms of the 5-year period.

While the use of the preceding charts will yield a computation based on mean values, it is sometimes more desirable to base a computation on the mode. The frequency distribution of precipitation amounts is usually skew (Figure 1), so that the mean does not correspond to the mode. The following method was used to develop a chart to indicate the probability that the precipitation amount will fall within a specified range. Observed precipitation amounts were divided into classes zero to five, with the following limits: 0–trace; 0.01–0.19 inch; 0.20–0.49 inch; 0.50–0.99 inch; 1.00–1.49 inches; and 1.50 inches and greater amounts. Similarly, computed values of C were divided arbitrarily into groups, numbered one to eight, with the following limits: 0.01–0.20 inch; 0.21–0.40 inch; 0.41–0.60 inch; 0.61–0.80 inch; 0.81–1.00 inch; 1.01–1.20 inches; 1.21–1.40 inches; 1.41 and greater amounts. Table 2 shows for each graded value of C the number of times that observed precipitation amounts fell into each of the five classes. In Table 3, which presents the same data in terms of cumulative frequencies and percents, frequency values shown for each graded value of C represent the number of times that observed precipitation fell into the corresponding precipitation class or a lower one; percentage values similarly indicate the probability of occurrence, based on the comparison of observed and computed amounts for these 73 cases. From Table 3, Figure 20 was prepared, using the graded values of forecast amount C and the cumulative percents of frequency as coordinates to plot the class numbers which represent the corresponding or lower amounts of observed precipitation. Distribution of these numbers on the diagram determined the slope of the curves which were drawn to divide the classes. Use of Figure 20 as a probability graph in the forecasting procedure is demonstrated in the next section of this paper.

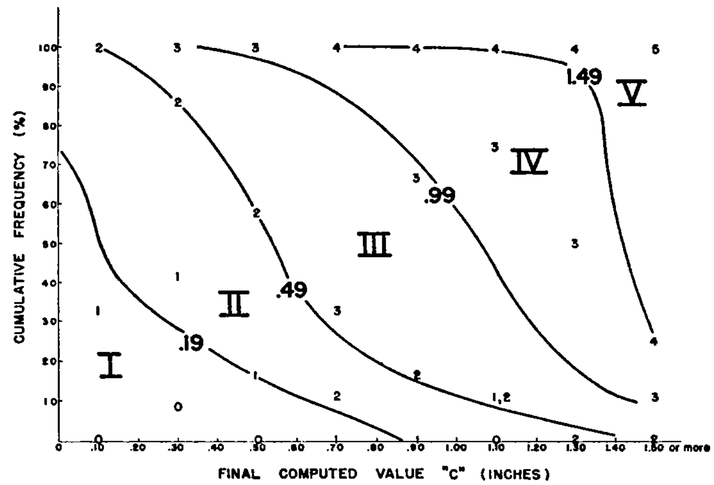

Figure 20.—Probability chart for determining precipitation class from C value, based on Table 3.

Table 2.—*Table showing the frequency of occurrence of each of six classes of precipitation as a function of the graded values of computed forecast value C*

	Class		GRADED VALUES OF C (Inches) .01–.20	.21–.40	.41–.60	.61–.80	.81–1.00	1.01–1.20	1.21–1.40	1.41 up	Total cases
OBSERVED PRECIPITATION (Inches)	0	0–Trace	0	2	0	0	0	0	0	0	2
	1	.01–.19	2	7	2	0	0	1	0	0	12
	2	.20–.49	4	10	5	1	1	0	0	0	21
	3	.50–.99	0	3	5	2	3	5	1	1	20
	4	1.00–1.49	--------	--------	--------	6	2	2	1	1	12
	5	1.50 or more	--------	--------	--------	--------	--------	--------	--------	6	6
Total cases			6	22	12	9	6	8	2	8	73

Table 3.—*Table showing the cumulative frequencies and percentages of occurrence of six precipitation classes as a function of the graded values of computed forecast value C*

	Class		GRADED VALUES OF C (Inches) .01–.20	.21–.40	.41–.60	.61–.80	.81–1.00	1.01–1.20	1.21–1.40	1.41 and more	Cumulative totals
OBSERVED PRECIPITATION (Inches)	0	0–Trace	0 0%	2 9%	0 0%	0 0%	0 0%	0 0%	0 0%	0 0%	2
	1 or less	.00–.19	2 33%	9 41%	2 17%	0 0%	0 0%	1 12%	0 0%	0 0%	14
	2 or less	.00–.49	6 100%	19 86%	7 58%	1 11%	1 17%	1 12%	0 0%	0 0%	35
	3 or less	.00–.99	6 100%	22 100%	12 100%	3 33%	4 67%	6 75%	1 50%	1 12%	55
	4 or less	.00–1.49	6 100%	22 100%	12 100%	9 100%	6 100%	8 100%	2 100%	2 25%	67
	5 or less	.00–1.50 and more	6 100%	22 100%	12 100%	9 100%	6 100%	8 100%	2 100%	8 100%	73
Total cases			6	22	12	9	6	8	2	8	73

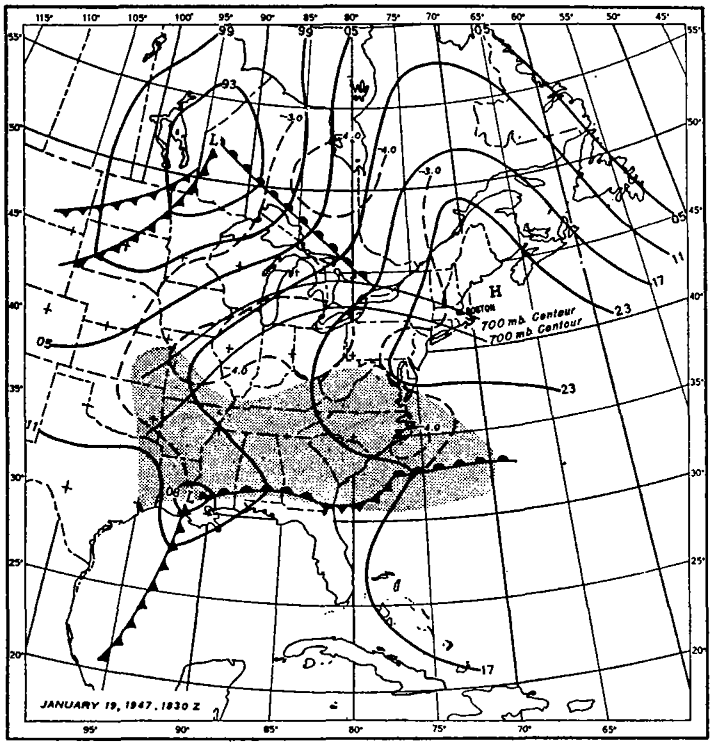

FIGURE 21.—Surface map used in example of objective forecast. Shaded area indicates where precipitation was occurring.

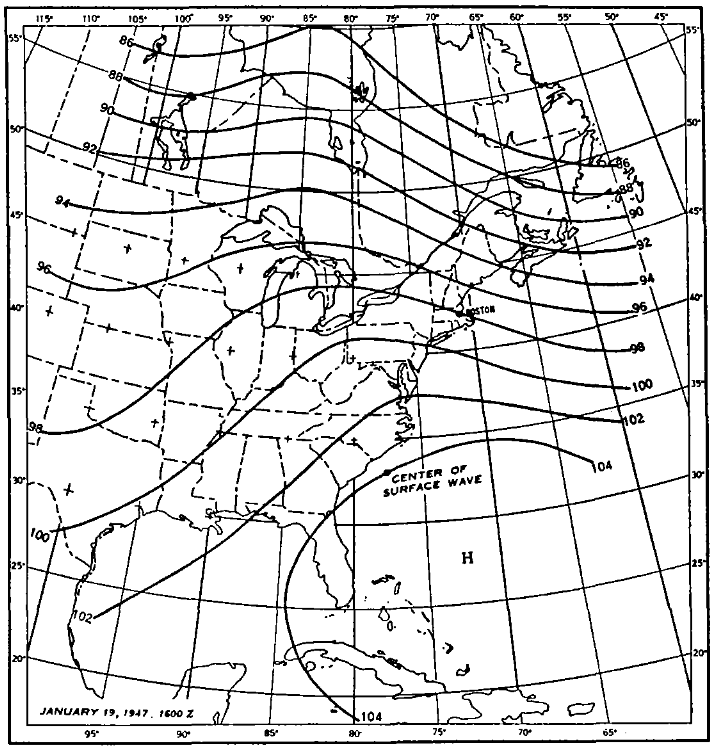

FIGURE 22.—700-mb. chart used in example of objective forecast, with location of surface pressure wave indicated.

EXAMPLE OF AN OBJECTIVE FORECAST

By using these constructed charts, at the time the storm first appears in the prescribed coastal area, the forecaster can compute the precipitation to be expected from a coastal storm. The routine of the computation for the objective forecast can be demonstrated by reference to the synoptic situation of January 19, 1947, at 1330 E. S. T. Figures 21, 22, and 23, show, respectively, the surface map, 700-mb. chart, and 850-mb. chart for this date.

1. Since precipitation is occurring upstream within the 700-mb. contouric channel, this case belongs in Group A.
2. Primary variables determined from these charts have the following values:

   $X_1=170°$=850-mb. wind direction above wave at 33° N., 77–1/2° W. (Figure 23)
   $X_2=240°$=700-mb. contour direction above wave (Figure 22)
   $X_3=33°$=latitude of surface storm (Figure 21)
   $X_4=36.5°$=minimum latitude (east of 95° W. long.) of 700-mb. contour line through Boston (Figure 22)
3. The pressure pattern, similar to that shown in Figure 9, indicates a Type 2 classification with reference to the secondary variables.
4. The derived functions and values determined from these parameters follows:

   $Y_1=1.10$ (from Figure 13, using X_1 and X_2)
   $Y_2=0.60$ (from Figure 14, using X_3 and X_4)
   $Z=0.90$ (from Figure 15, using Y_1 and Y_2)
   $C=1.19$ (from Figure 17)

   The computed precipitation amount of 1.19 inches for the forecast compares favorably with the observed amount for this storm, which was 1.05 inches.
5. Figure 20 is used to obtain an indication of the most likely class in which the precipitation will occur; from this chart the following is noted, when C=1.19 inches:
   (a) There is a zero chance that the amount of precipitation will be 0.19 inch or less.
   (b) There are 6 chances in 100 that the amount will be 0.49 inch or less.
   (c) There is a 30-percent chance that the amount will be 0.99 inch or less; and 24 (30 minus 6) chances in 100 that the amount will be greater than 0.49 inch and less than 1.00 inch.
   (d) There are 99 chances in 100 that the amount will be 1.49 inches or less; and there are 69 (99 minus 30) chances in 100 that the observed amount will be greater than 0.99 inch and less than 1.50 inches.
   (e) There is only one chance (100 minus 99) in 100 that the observed amount will be greater than 1.49 inches.

The highest probability, when C=1.19 inches, is for the precipitation amount to occur in Class IV (1.00–1.49 inches). The amount actually observed, 1.05 inches, is in this group.

FIGURE 23.—850-mb. chart used in example of objective forecast, with location of surface pressure wave indicated.

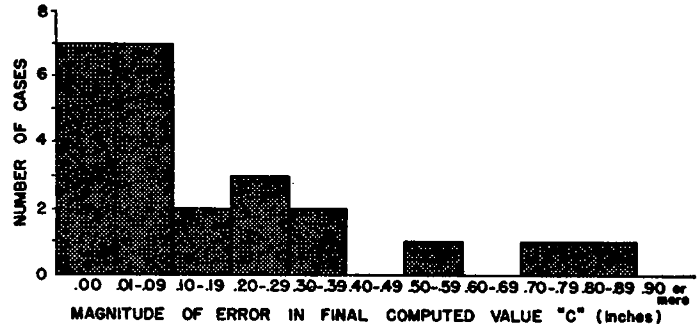

FIGURE 24.—Distribution of errors in computed forecast value, C, for 24 cases of coastal storms used as test data.

TEST OF METHOD ON INDEPENDENT DATA

The 24 storms included in the test data contained 16 cases in the Group A map classification or in Group B_1 (all followed by precipitation at Boston), and 8 cases in Group B_2. Seven of the latter resulted in no precipitation at Boston, and one (February 24, 1946) was followed by 0.02 inch.

Data for all variables of these 24 test cases and resulting computed forecast amounts are shown in Table 4. The correlation between the observed and forecast amounts (last two columns) was 0.85, and the standard error of estimate was 0.29 inch. Figure 24, the distribution of errors in the 24 tests forecasts, shows that when only the 16 cases involving precipitation were considered, the correlation between computed forecast amounts and observed amounts was 0.71, and the standard error of estimate was 0.36 inch. The significance of the secondary variables is indicated by the fact that the correlation of 0.71 is reduced to 0.58 when these variables are not used.

Table 5 is a contingency table based on the probability curves of Figure 20, as applied to the computed (C) values of the 24 test cases. This tabulation reveals 14 cases having no class error; 8 involving 1 class error; only 2 cases erring by 2 classes; and none with greater errors.

TABLE 4.—*Tabulation of computations made for forecasting 24 test cases, and corresponding observed precipitation amounts*

Date	Time (Z)	Map group	Variables							ΔP*	Pressure type	Computed amounts (C)	Observed amounts
			X_1	X_2	Y_1	X_3	X_4	Y_2	Z				
March 1947													
1	0600	A	210	260	0.50	31	36	0.80	0.65		2	0.93	1.50
8	0600	B_2										.00	T
11	1200	B_2										.00	.00
19	1800	B_2										.00	.00
28	0600	B_2										.00	.00
February 1946													
6	1200	A	230	250	.40	35	35	.75	.60		3	.48	.59
10	1800	B_2										.00	.00
19	1800	A	170	220	1.25	35	34	.90	1.10		3	.86	1.08
23	0000	A	260	270	.15	38	50	.10	.15	20	1	.05	.05
24	0600	B_2										.00	.02
26	1800	A	260	270	.15	40	38	.35	.30		3	.25	.25
28	0000	A	230	250	.40	40	35	.50	.45		2	.67	.85
December 1944													
8	0000	A	190	210	1.30	33	29	1.50	1.50		3	1.16	.38
11	0600	A	180	230	1.20	32	30	1.50	1.50		2	1.50	1.16
19	0000	A	270	260	.15	39	42	.20	.20		2	.29	.30
27	1800	A	230	250	.40	36	37	.45	.45		2	.67	.76
29	1800	B_2										.00	.00
November 1942													
3	0000	A	250	250	.30	38	39.5	.35	.35		3	.29	.69
23	1200	B_1	190	230	1.10	32	32	1.40	1.35		2	1.50	1.50
January 1943													
4	0600	A	250	250	.30	39	39	.35	.35	15	1	.20	.44
8	0600	B_2										.00	.00
18	1200	A	260	270	.15	38	33	.90	.60		2	.87	.89
28	0600	A	180	210	1.40	33	28	1.50	1.50		2	1.50	1.49
30	1200	A	240	240	.40	33	30	1.50	1.10		2	1.37	.56

* Pressure difference between Caribou, Maine, and Gander, Newfoundland, taken from surface map.

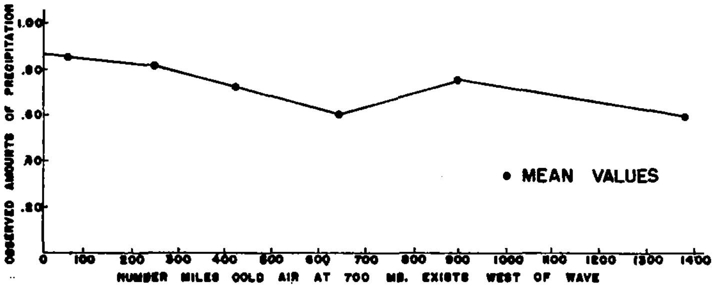

FIGURE 25.—Charts showing correlation of mean values of observed precipitation amounts with values of the number of miles that cold air advection at 700-mb. level extends west of surface pressure wave.

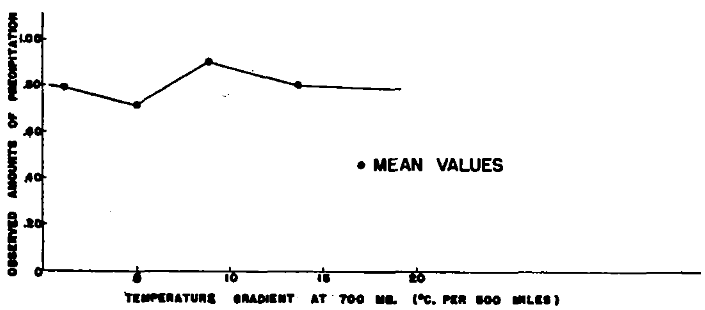

FIGURE 26.—Chart showing correlation of values of temperature gradient at 700-mb. level with mean values of observed amounts of precipitation.

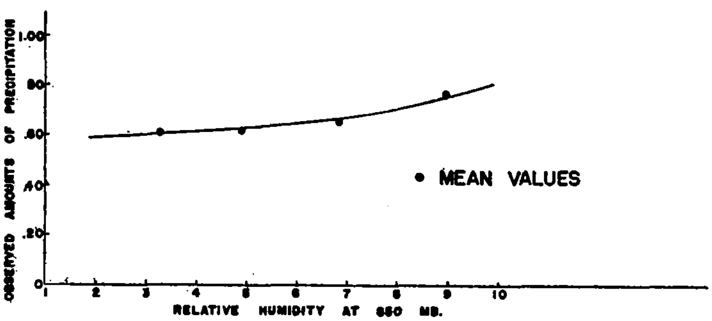

FIGURE 27.—Chart showing correlation of mean values of observed relative humidity at 850 mb. with mean values of observed precipitation amounts.

TESTS OF OTHER VARIABLES

In the course of the selection of significant meteorological variables to be related to precipitation amounts, several of those which experienced forecasters have believed to be of value in making precipitation forecasts were tested. Use of a simple graphical method for relating these upper-air factors to observed amounts of precipitation demonstrated that for this type of forecasting they were, on the whole, insignificant. Charts were constructed for such variables as (a) cold-air advection at 700-mb., (b) the 700-mb. temperature gradient, and (c) the moisture at 850 mb. In each case the variable to be tested was first plotted on a graph as the abscissa, and the corresponding precipitation amounts were plotted as the ordinate. Then the variable was divided into several sections or classes, and the mean amount of precipitation was determined for each. The curve which was finally drawn from these mean values was taken to indicate the degree of dependence of the precipitation amounts upon the variable being tested. Because this method of testing was elementary, the results cannot be considered conclusive; the joint relationships provide a field for further research.

COLD AIR ADVECTION AT 700 MB.

The influx of colder air from the west at the 700-mb. level has been suspected by forecasters of being the explosive necessary to set off wave developments. The subsequent advection of colder air to a position over the warm coastal waters has been assumed to have two major effects: (a) of increasing the potential energy of the area; (b) of increasing the vertical instability of the air (that is, the steepening of the temperature lapse rate). Since both effects might probably lead to increased precipitation, a test of the effect of this variable on precipitation amounts was made, following the graphical method outlined above. Figure 25 is the graph resulting from plotting the observed precipitation against the number of miles the cold air advection at 700 mb. extended west of the surface wave, as determined from the orientation of isotherms and contours. Contrary to the belief prevalent among forecasters, this diagram indicates little relationship between the proximity of cold air advection at 700 mb. and subsequent precipitation amounts at Boston.

TABLE 5.—*Contingency table based on the probability curves of Figure 20, for the 24 test cases*

	COMPUTED PRECIPITATION (Inches)						
	0—Trace	.01—.19	.20—.49	.50—.99	1.00—1.49	1.50 or more	Total cases
OBSERVED PRECIPITATION (Inches) 0—Trace	7						7
.01—.19	1	1					2
.20—.49		1	2		1		4
.50—.99			2	3	1		6
1.00—1.49				1		2	3
1.50— or more				1		1	2
Total cases	8	2	4	5	2	3	24

In 61 cases for which completely analyzed upper-air charts were available, the cold air advection was further tested by extracting from the 700-mb. chart for each case the subsequent 12-hour temperature change over the original position of the storm. The following results pointed to no generally significant effect.

(a) 27 cases showed a falling temperature change.
(b) 34 cases showed rising temperature or no change.

THE 700-MB. TEMPERATURE GRADIENT

The 700-mb. temperature gradient, expressed in degrees centigrade per 500 miles, was determined by getting the temperature difference between a point near the storm and one 500 miles back into the cold air. The curve shown in Figure 26 indicates little apparent relationship between the temperature gradient as determined here and subsequent precipitation amounts recorded in the Boston area for 43 cases.

MOISTURE AT 850 MB.

The amount of moisture near the 5,000-foot level has also been suggested as a useful factor in determining future precipitation amounts. In this test the mean relative humidity, used as a measure of the moisture content, was determined along a path from a position directly over the storm to a point 300 miles upwind, unless the path intersected the trough in a shorter distance; in that event, the mean relative humidity was determined only as far as the trough. The plotted curve of Figure 27, based on 61 cases, shows that the relative humidity measured in this way has little relationship to the precipitation amounts. Substitution of mixing ratio for the relative humidity gave similar negative results.

ADDITIONAL VARIABLES

Several other variables tested were: (a) the distance between the forecast area and the path of the storm, measured along a line normal to the storm path; (b) the deepening of the storm between the time of beginning of the forecast period and the time the storm passes the forecast point; (c) the length of the precipitation period. These three variables were found to be significantly related to the precipitation amounts. Unfortunately, these variables, which themselves must be forecast, are usually as difficult to determine as is the precipitation amount.

CONCLUSIONS

The results of this study clearly demonstrate that objective techniques can be utilized advantageously in forecasting precipitation amounts for winter coastal storms. Parameters X_1 (the 850-mb. wind direction above the storm), X_2 (the 700-mb. contour direction over the storm), X_3 (the latitude of the surface storm), and X_4 (the minimum latitude of the 700-mb. contour through Boston) are all significant factors that can be easily determined and effectively used for objective forecasts. However, it is also evident that the introduction of the secondary variables entails some loss in simplicity and objectivity of method, upon which so much emphasis has been laid, although elimination of the secondary variables is not justifiable in the light of forecast results. For instance, the correlation coefficients between the observed and computed amounts of precipitation for those cases used to develop the study, including no-rain cases, were 0.74 when the primary variables alone were used, but 0.84 when the secondary variables also were applied. Corresponding correlation coefficients for the test data were 0.85 when all variables were used, but only 0.78 when primary variables alone were employed.

The fixed periods and the precipitation classes of the conventional, official forecasts issued by the Boston Forecast Center prevented comparison of those forecasts with the storm total forecasts obtained by the objective method. However, the correlation of 0.85 for the test cases might be compared with the 0.69 correlation Brier obtained in his application of objective techniques for the T. V. A. Basin forecasts.

The seemingly insignificant relationship between the precipitation amounts and some of the upper-air factors must be interpreted with caution. The results, which apply only to this study, do not necessarily lend themselves to generalization.

There are, of course, other factors influencing quantitative precipitation which have not been utilized in this study. Some, such as the processes of vertical motion and divergence, still await some effective means of measurement.

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